

Mobile Source Air Toxics: Project-Level Emissions Analyses and Emissions Sensitivity Testing

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Abstract

Background: Mobile source air toxics (MSATs) are emitted by the transportation sector and are hazardous to human health. Studies have identified diesel particulate matter (DPM) to be responsible for the vast majority of the urban air toxics risk in California. Federal requirements mandate project-level MSAT emissions assessments for highway improvement projects with high potential MSAT effects, such as capacity expansion projects in proximity to populated areas. Understanding how traffic parameters influence MSAT emissions can assist project analysts in designing transportation projects to minimize local urban air quality impacts.

Methods: This study used a California-based emissions modeling tool, CT-EMFAC, to assess how project level MSAT emissions can change over time and also tested emissions sensitivity to changes in traffic volumes, speeds, and fleet composition. The investigation employed a hypothetical 6.7-mile freeway segment located in southern California's South Coast Air Basin (SCAB); the traffic activity data were derived from real-world information obtained from the California Department of Transportation. In addition, two speed post-processing methods, a Bureau of Public Roads function and a calculation method used by the Texas Transportation Institute, were employed to assess MSAT emissions sensitivity to speed calculation variations.

Results: The findings showed that emissions more than doubled in 2004 and increased by a factor of two to four in 2030 when traffic volumes increased 30% above base-case conditions. The non-linear shift in emissions was a function of decreased travel speeds and increased g/mi emission rates that accompanied increased traffic volumes. Fleet composition, in terms of proportion of trucks, was also shown to affect MSAT emissions, especially for DPM and aldehydes. Under some scenarios, the choice of the speed calculation method had a greater impact on MSAT emissions than 26 years of fleet turnover.

About The U.C. Davis-Caltrans Air Quality Project

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Mission: The Air Quality Project (AQP) seeks to advance understanding of transportation related air quality problems, develop advanced modeling and analysis capability within the transportation and air quality planning community, and foster collaboration among agencies to improve mobility and achieve air quality goals.

History: Since the 1990s, the U.S. Federal Highway Administration and Caltrans have funded the AQP to provide transportation-related air quality support. Caltrans and AQP researchers identify and resolve issues that could slow clean air progress and transportation improvements.

Accessibility: AQP written materials and software tools are distributed through our website, peer-reviewed publications, conference presentations, training classes, formal reports and technical memoranda, and periodic newsletters.

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1. INTRODUCTION

1.1 Study Objectives

The purpose of this study was to evaluate how changes in traffic activity affect mobile source air toxics (MSAT) emissions and to illustrate project-level MSAT emissions inventories for base and future years using a hypothetical freeway widening project. Specifically, the study tested the sensitivity of MSAT running exhaust emissions to traffic volumes, fleet mix, and vehicle speeds using a California-based project-level mobile source emissions modeling tool called CT-EMFAC.

Average speed used for emissions analysis is often calculated using different speed post-processing methods. Variations in travel speed calculations have an effect on MSAT emissions estimates; this study explored the differences between two selected speed calculation techniques for developing project-level MSAT emissions estimates. In addition, MSAT emissions comparisons were performed among three hypothetical highway improvement scenarios, and results were compared to no-build alternatives for base, opening, and horizon years. The work was motivated by federal requirements to complete project-level MSAT emissions evaluations.¹ The study sought to provide project analysts with a deeper understanding of the factors that affect MSAT emissions and to enhance consideration of project design options for reducing real-world operating emissions.

1.2 MSATs Background

MSATs are an important constituent of urban-scale and near-road pollution problems. MSATs are present in gasoline and its additives and can escape into the air through evaporation or

¹ See, for example: <http://www.fhwa.dot.gov/environment/airtoxic/100109guidmem.pdf>.

combustion (EPA, 2008). Some MSATs are also formed secondarily through chemical reactions in the atmosphere. Although some MSATs can be found in food and water, inhalation is the dominant pathway of human exposure, particularly in areas with heavy motor vehicle traffic and around fuel filling stations (DHHS, 2007).

According to the U.S. Environmental Protection Agency (EPA) National-Scale Air Toxics Assessment (NATA), mobile sources were responsible for about 47% of total outdoor toxic emissions, almost 30% of the population cancer risk and 77% of non-cancer risk in 2002 (EPA, 2009). In addition, people who live or work near major roads or live in homes with attached garages are likely to have higher exposures and risk, which were not reflected in NATA (EPA, 2007). As of 2004, approximately 37 million people lived within 300 feet of a four-or-more lane highway, railroad, or airport, according to the U.S. Census Bureau's American Housing Survey;² therefore potential exposure to near-source air toxics is a significant concern.

A growing body of literature has linked road proximity to increased pollutant concentrations and adverse health impacts. Some of the most-cited near-road study findings include research completed near southern California freeways. For example, a southern California study by Zhu et al. (2002) found that black carbon and total particle number concentration emissions are at their highest concentration near-roads and decrease to background level at approximately 300 meters. In addition, other California-based studies have contributed to the near-road health-effects literature. For example, Kim et al. (2004) found that asthma symptoms in children were related to proximity of high traffic roadways in the San Francisco Bay Area. English et al. (1999) found that medical visits increased for children living within 550 feet of heavily trafficked roads in the San Diego area. It is important to note that

² For more detailed data, see: <http://www.census.gov/prod/2006pubs/h150-05.pdf>.

different microenvironments can dominate toxics exposure for individuals. Individual exposure can vary substantially for occupants in moving vehicles, depending on the quantity of emissions originating from other vehicles operating ahead of the vehicles in which the occupants are located (Fruin et al., 2004).

Among MSATs, diesel particulate matter (DPM) is a special concern. Diesel exhaust is known to contain over 40 cancer-causing substances that are absorbed on soot particles emitted by diesel cars or trucks. The California Air Resources Board (CARB) identified DPM as a toxic air contaminant (CA EPA, 1998) and EPA found that diesel exhaust presented a chronic respiratory hazard, and was likely to be carcinogenic to humans (EPA, 2002). The Multiple Air Toxics Exposure Study III (MATES III), conducted in the greater Los Angeles area, in 2004 and 2005, reported that diesel exhaust accounted for about 84% of the total air toxics related risk (SCAQMD, 2008). In addition, MATES III found that, although the overall population-weighted air toxics risk was reduced 8% between 1999 and 2007, diesel particulate concentrations increased near ports and transportation corridors during that same period.

1.3 Regulations Related to MSATs

Federal agencies have mandated a variety of fuel and vehicle-based controls to reduce MSAT emissions. In 2001, EPA issued a Final Rule (Controlling Emissions of Hazardous Air Pollutants from Mobile Sources) that identified six priority MSATs: diesel exhaust organic gases (DEOG, including diesel particulate matter, or DPM), formaldehyde, 1,3-butadiene, benzene, acrolein, and acetaldehyde. The 2001 rule also mandated gasoline-related toxics emissions performance requirements.³ In 2006, the U.S. Federal Highway Administration (FHWA) published guidance that required project-level MSAT emissions assessment (Burbank,

³ See: <http://www.epa.gov/otaq/regs/toxics/toxicfrm.pdf>.

2006). In 2007, EPA updated its MSAT requirements and modified the list of priority pollutants. The 2007 regulation addressed non-methane hydrocarbon exhaust emissions from passenger vehicles at cold temperatures, evaporative emissions from passenger vehicles, and the benzene content of gasoline.⁴ In 2009, FHWA updated its MSAT guidance to reflect the most recent EPA MSAT rule makings (Marchese, 2009).

On the state level, California agencies have taken numerous steps to reduce MSAT emissions from mobile sources, including adoption by CARB in 2000 of a diesel risk reduction plan to reduce DPM emissions and associated health risks 75 percent by 2010 and 85 percent by 2020.⁵ Other example actions include requirements to limit school bus idling, especially near schools (13 CCR Chapter 10 § 2480), and modification of the California Education Code (Section 17213) to restrict placement of new schools within 500 feet of freeway segments, urban roadways with daily a volume of 100,000 vehicles, or rural roadways with a daily volume of 50,000 vehicles (CDE, 2009).

As a result of state and federal regulatory actions, urban-area on-road MSAT emissions have generally been decreasing and are projected to decline further through the 2020s due to fleet turnover to cleaner-operating vehicles and the introduction of cleaner burning diesel and gasoline fuels (e.g., Burbank, 2006; Marchese, 2009). However, under some conditions traffic activity has the potential to contribute to localized pollutant concentrations that exceed urban background conditions. In addition, MSATs can contribute to tropospheric ozone formation, and DPM is a subset of fine particulate matter (PM_{2.5}); ozone and PM_{2.5} are criteria pollutants subject to National Ambient Air Quality Standards (NAASQ). Therefore, there is an ongoing need to produce estimate MSAT emissions at the project level, as well as to track and address regional-

⁴ For additional information, see: <http://www.epa.gov/otaq/toxics.htm#regs>.

⁵ See: <http://arbis.arb.ca.gov/diesel/documents/rrpFinal.pdf>.

scale on-road vehicle contributions to MSAT and criteria pollutant concentrations. This study focused on providing new insights to help project analysts consider how traffic parameters influence localized MSAT emissions.

1.4 MSAT Emissions Modeling

Generally, two tools have been used to estimate on-road vehicle emissions: EPA's MOBILE6.2 on-road vehicle emissions model, used in states other than California, and CARB's EMFAC on-road emissions model, used in California. The two tools were developed over many years in response to national and California vehicle emission standards. In December 2009, EPA released a new mobile source emission model, called MOVES (as of this writing, the latest version was MOVES2010). During 2010 and 2011, states other than California will transition from using MOBILE to using MOVES to estimate on-road vehicle emissions contributing to climate change, criteria pollutant, and MSAT-related pollution problems. In California, CARB's EMFAC2007 model is used for estimating on-road mobile source emissions; however, it does not provide an estimate of MSAT emissions.

In response to the lack of a California-specific MSAT emissions modeling tool, researchers from the University of California, Davis worked in collaboration with the staff from the California Department of Transportation (Caltrans) and CARB to develop the CT-EMFAC emissions modeling tool (Wu et al., 2007). This study used CT-EMFAC Version 2.6 (released May 29, 2008) to estimate emissions for the six priority MSATs (DPM, formaldehyde, 1,3-butadiene, benzene, acrolein, and acetaldehyde) identified in EPA's 2001 MSAT rule.⁶ It may be applied at the project level with user inputs of speed-based vehicle miles traveled (VMT).

⁶ CT-EMFAC also provides emissions information for other key urban-scale pollutants (TOG, CO, NO_x, SO_x, PM₁₀, or PM_{2.5}) and CO₂.

2. CASE STUDY AND METHODOLOGY

This section discusses important steps in MSAT emissions evaluation. Section 2.1 describes the case-study and identifies project characteristics useful in the analysis. Section 2.2 focuses on speed post-processing techniques and speed calculation method selection. The last section, Section 2.3, covers emissions modeling using CT-EMFAC. Figure 1 is a visual representation of the project-level MSAT emissions evaluation process.

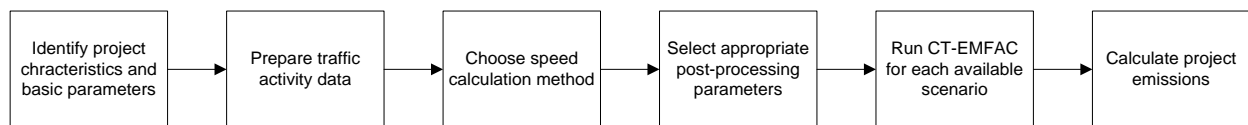


Figure 1. Project-level MSAT emissions evaluation

2.1 Case Study Description

This study used data obtained from Caltrans to create a hypothetical 6.7-mile freeway improvement project located in Los Angeles County, California. The case study assumed base case conditions that included three mixed-flow freeway travel lanes operating in each direction for a 2004 base year. The case study hypothesized future-year base case (i.e., no-build) conditions, as well three possible future-year build alternatives: the addition of (1) one mixed flow (MF) and one high occupancy vehicle (HOV) lane (4MF+1HOV); (2) one MF and two HOV lanes (4MF+2HOV); or (3) two MF and one HOV lane (5MF+1HOV). Future-year no-build and build alternatives were analyzed for year 2013 (the assumed project opening year for the build scenarios) and a 2030 horizon year.

Base case (no-build) travel volumes and fleet mix reflected real-world project conditions from recent southern California freeway improvement projects: a 26% overall increase in

forecasted traffic volumes from 2004 to 2030, and a growing share of overall travel by medium-duty and larger trucks (from 9% of 2004 activity to 13% of 2030 activity). Caltrans made available example project-specific data that showed increasing traffic volumes due to capacity expansion from the addition of new lanes. Accordingly, our case study assumed that build alternatives which increased capacity resulted in higher traffic volumes compared to no-build conditions (see Section 2.2 for more information). Caltrans activity data were used to construct 2004 and 2030 scenarios; year 2013 traffic data were developed based on linear interpolation.

In addition to testing how base case and project build alternatives affected MSAT emissions, we also tested the sensitivity of modeled emission outcomes to various traffic composition and speed assumptions. The sensitivity analyses focused on peak period conditions for a 2004 base case and a 2030 no-build alternative. The scenario comparisons were conducted using total traffic volumes and average speed data for all lanes (both peak and off-peak) for 2004 (base year), 2013 and 2030.

2.2 Speed Post-Processing

Emissions are influenced by key traffic variables; one such variable is vehicle speed. For emission assessments, estimates of regional-scale travel speed are often post-processed to yield more refined estimates of project-level travel speeds. A number of speed post-processing methods have been discussed in the literature (Dowling et al., 1996; HCM, 2000; ICF Consulting, 2004; Bai et al., 2007). In this study, project-specific travel speeds were calculated using two relatively simple and widely used speed post-processing techniques discussed by Dowling et al. (1996). The first method—the Bureau of Public Roads (BPR) function—was developed in the 1960s; it can be used to obtain speeds on individual freeway links, as well as to determine average speed by functional class. As shown in Equation 1, the BPR function models

the average highway speed (s) by adjusting the free-flow speed (s_f), as traffic volume (v) approaches roadway capacity (c),

$$s = \frac{s_f}{1 + a(v/c)^b} \quad (1)$$

where the two parameters, a and b are constants that can be calibrated to reflect local conditions or specific roadway functional class. This study assumed $a = 0.2$ and $b = 10$ (values that the literature has defined as appropriate for calculating average speeds of freeway segments; see: Skabardonis and Dowling, 1997).

The second method chosen to estimate congested freeway speeds was the Texas Transportation Institute (TTI) function (NHI, 2003; ICF Consulting, 2004; Claggett and Miller, 2006). The basis of this method is the harmonic mean of free-flow speed and delay. The TTI speed calculation is,

$$s = \frac{60}{\frac{60}{s_f} + delay} \quad (2)$$

where $delay$ is

$$delay = \min[A \exp^{B(v/c)}, M] \quad (3)$$

and the coefficients $A = 0.015$ and $B = 3.5$. M is the maximum number of minutes of delay per mile and is equal to five for high-capacity facilities such as the freeway segments assessed in this study. Note that one shortcoming of this formula is that it creates a minimum possible speed that can be calculated for a freeway link. When the v/c ratio is high, the delay will always be five minutes, resulting in the same speed approximation independent of further volume increases for a given capacity.

The parameters used for calculating average speeds in this study (e.g., a/b of the BPR function and A/B of the TTI method) are based on values cited previously in the literature. It should be noted, however, that values may be different in practice based on local conditions. This purpose of this study was not to test the suitability of various parameters or speed post-processing techniques, but rather to investigate how the selection of a speed estimation method could affect estimated speeds and emissions.

Both the BPR and TTI methods require input of volume, capacity, and free-flow speed. To develop speed estimates, total vehicle traffic volume from our data set was translated into passenger car-equivalent flow rate (V_p) in passenger vehicles per hour per lane.

$$V_p = \frac{V}{PHF * N * f_{hv} * f_p} \quad (4)$$

where PHF, the peak hour factor, is equal to 0.9; N, the number of lanes in both directions, is six; f_{hv} , the heavy vehicle adjustment factor, is equal to 0.96 (i.e., trucks were assumed to be equivalent to 1.5 passenger vehicles); f_p is the driver population factor that is equal to one during peak hour commute. Further assumptions were also made for the free-flow speed (65 mph) and the associated roadway capacity (2,350 vehicles per hour per lane) based on the Highway Capacity Manual (2000).

The BPR formula was used to compare speed estimates with the TTI method and assess MSAT emissions variations that would result from using one post-processing technique over the other (Section 3.2). For consistency, the TTI method was chosen to calculate travel speeds for both the sensitivity analysis and the evaluation of the case study build alternatives. Traffic activity data for the highway project case study is summarized in Table 1.

Table 1. Case study traffic activity data

Year	Scenario	Lanes	Peak Period			Off-peak period			Total
			Daily Volume	Truck Volume	Speed, mph	Daily Volume	Truck Volume	Speed, mph	Daily Volume
2004	No-build*	3 MF	78,349	7,356	38	105,899	9,942	60	184,248
2013	No-build	3 MF	85,273	9,138	32	113,141	15,073	59	198,415
	Build	4 MF	90,013	10,108	45	113,405	16,176	61	229,305
		1HOV	12,677	0	56	13,210	0	63	
	Build	4 MF	89,483	10,045	46	113,196	16,116	61	235,085
		2 HOV	17,148	0	60	15,259	0	63	
	Build	5 MF	95,176	10,580	52	117,915	16,594	62	235,623
		1 HOV	11,924	0	57	10,608	0	63	
	No-build*	3 MF	98,352	12,505	22	126,821	24,765	57	225,174
2030	Build	4 MF	112,045	15,308	32	127,584	27,950	60	291,403
		1HOV	25,353	0	32	26,421	0	60	
	Build	4 MF	110,512	15,125	33	126,980	27,777	60	302,305
		2 HOV	34,295	0	47	30,518	0	62	
	Build	5 MF	126,960	16,670	39	140,611	29,159	61	312,635
		1 HOV	23,849	0	39	21,215	0	61	

Note: Speed estimates are based on the TTI method. Year 2013 MF lane volumes are linearly interpolated based on 2004 and 2030 data. * Scenarios used as base cases for the sensitivity analyses.

2.3 MSAT Emissions Modeling Using CT-EMFAC

This study used CT-EMFAC (version 2.6, May 2008) to model annual project-level MSAT emissions (Wu et al., 2007). The program includes a database of year-specific composite emission factors corresponding to combinations of temperature, relative humidity, speed, vehicle class, and technology type specific to particular geographic areas in California. The database encompasses 39 calendar years (2002-2040) and 93 geographical areas. A user can choose to model emissions for the whole state, a specific air basin, or individual counties.

The minimum data needed to conduct an analysis includes the analysis year, traffic volume, truck percentage, and average traffic speed. By varying the volume and truck

percentage and the subsequent speed estimates, the emissions sensitivity of the six priority MSAT pollutants can be evaluated using outputs from CT-EMFAC for each test scenario.

The CT-EMFAC program runs in two steps. The first is the “Emission Factors” step (see Figure 2) that allows a user to create an analysis scenario based on user-specific parameters (geographic area, analysis year, season, pollutants of interest, and vehicle mix).

CT-EMFAC Version 2.6 May 29, 2008

Help

Title Emission Factors Emission Calculations

Scenario Title: (a title must be entered)

Geographic Area: ☒ State ☐ Air Basin ☐ County

Analysis Year:

Season: ☐ Summer ☐ Winter ☐ Annual

Vehicle Mix: ☒ Use Default ☐ Input Percentage

Trucks (%) Others (%) Sum (%) 100

Pollutants: ☐ TOG ☐ CO ☐ NOX ☐ SOX ☐ CO2
☐ PM10 ☐ PM2.5 ☐ Diesel PM
☐ Benzene ☐ Acrolein ☐ Acetaldehyde ☐ Formaldehyde ☐ 1,3-Butadiene

Toxics Speciation: ☐ EPA Factors ☒ CARB Factors

Only CARB speciation factors are available in the current CT-EMFAC version

RUN RESET NEXT

! Please click "Run" before you click "Next"

Figure 2. CT-EMFAC “Emission Factors” page

The model's input for fleet composition consists of two groups: trucks (medium-duty and above vehicles) and others (primarily passenger cars and light-duty trucks). The truck group includes both diesel and non-diesel trucks and the program automatically apportions the truck fleet into appropriate fuel-specific fractions using default data from CARB's EMFAC2007 model. Consistent with CT-EMFAC, all medium-duty and above vehicles, regardless of fuel type, are referred to as "trucks" in this study. See all vehicle classes in Table 2.

Table 2. Vehicle class distribution for CT-EMFAC

Vehicle Class	Fuel Type	Code	Description	Weight Class (pounds)	Abbr.	CT-EMFAC Vehicle Designation
1	Gas, Diesel, Electric	PC	Passenger Cars	All	LDA	Others
2	Gas, Diesel, Electric	T1	Light-Duty Trucks	0-3750	LDT1	
3	Gas, Diesel	T2	Light-Duty Trucks	3751-5750	LDT2	
4	Gas, Diesel	T3	Medium-Duty Trucks	5751-8500	MDV	Trucks
5	Gas, Diesel	T4	Light-Heavy-Duty Trucks	8501-10000	LHDT1	
6	Gas, Diesel	T5	Light-Heavy-Duty Trucks	10001-14000	LHDT2	
7	Gas, Diesel	T6	Medium-Heavy-Duty Truck	14001-33000	MHDT	
8	Gas, Diesel	T7	Heavy-Heavy-Duty Trucks	33001-60000	HHDT	
9	Gas, Diesel	OB	Other Buses	All	OB	Others
10	Diesel	UB	Urban Buses	All	UB	
11	Gas	MC	Motorcycles	All	MCY	
12	Gas, Diesel	SB	School Buses	All	SBUS	
13	Gas, Diesel	MH	Motor Homes	All	MH	

Source: Wu, et al. (2007).

The next step is "Emission Calculations". The software is designed to calculate emission inventories based on the composite emission factors obtained in the first step. CT-EMFAC allows the user to input project-specific travel activity data (Figure 3). The tool then calculates

total emissions using either total VMT data or traffic volume with road segment length data, depending on data availability. This study used the latter method.

CT-EMFAC Version 2.6 May 29, 2008

Help

Title Emission Factors **Emission Calculations**

Scenario Title: (a title must be entered)

Emission Factors: ☐ Current ☐ Choose From a Saved Scenario

Travel Activities: ☒ VMT ☐ Volume and Road Length

Peak

	Total VMT	Volume (vph)	Road Length (mi)	Number of Hours					
VMT Distribution by Speed (mph)	5	10	15	20	25	30	35	40	
	%	%	%	%	%	%	%	%	%
	45	50	55	60	65	70	>70	Sum	
	%	%	%	%	%	%	%	%	100 %
Average Vehicle Idling Time (min/hr)									(currently unavailable)

Off Peak

	Total VMT	Volume (vph)	Road Length (mi)	Number of Hours					
VMT Distribution by Speed (mph)	5	10	15	20	25	30	35	40	
	%	%	%	%	%	%	%	%	%
	45	50	55	60	65	70	>70	Sum	
	%	%	%	%	%	%	%	%	100 %
Average Vehicle Idling Time (min/hr)									(currently unavailable)

Total Number of Hours: 24

Only available pollutants in EF file appear checked below

Pollutants: ☐ TOG ☐ CO ☐ NOX ☐ SOX ☐ CO2 ☐ PM10 ☐ PM2.5 ☐ Diesel PM ☐ Benzene ☐ Acrolein ☐ Acetaldehyde ☐ Formaldehyde ☐ 1,3-Butadiene

RUN RESET

Figure 3. CT-EMFAC “Emission Calculations” page

To calculate daily emissions, a user can input both peak and off-peak travel activities in the “Emission Calculations” tab in one single run. However, if fleet composition varies for peak and off-peak time periods (as assumed in this study), the two periods need to be run separately.

The output includes fleet-average g/mi emission factors by pollutant for 13 speed bins with 5 mph increments. For this study, emission factors were linearly interpolated within a given speed bin to obtain continuous speed-based emission factors appropriate for the sensitivity analyses.

CT-EMFAC calculates emission factors for gaseous MSATs (excluding DPM) based on toxics speciation factors supplied by CARB. A speciation factor represents the ratio of emissions of a specific MSAT to total organic gas (TOG) emissions. An emission factor for a particular MSAT can be obtained by multiplying the TOG emission factor by the speciation factor associated with the vehicle class, technology type, and fuel type. These calculations, embedded in the program, are specific to each calendar year, season, geographic area, and emission process (stabilized running exhaust or running loss). The DPM composite emission factors are calculated by taking a weighted average of all emission factors for diesel trucks. The factors are then combined with percentages of diesel trucks and diesel non-trucks in the whole fleet to calculate fleet-average DPM composite emission factors.

The CT-EMFAC version employed here includes two important data limitations. At the time CT-EMFAC was developed, CARB did not have acrolein speciation factors applicable to diesel vehicles. Thus, CT-EMFAC (and, consequently, this study) reports acrolein emissions solely for gasoline-powered vehicles. Others, for example, Vernmeire (1991) and U.S. Department of Health and Human Services (2007), have identified that diesel-powered vehicles emit acrolein. Therefore, the results reported here should be considered a partial assessment of the sensitivity of acrolein emissions to varying fleet characteristics. Also, due to a lack of data, CARB assumed that speciation factors for the five gaseous MSATs associated with the diesel fleet remain constant over time. In contrast, CARB's gasoline-vehicle speciation factors for

gaseous MSATs declines over time (e.g., the fraction of gasoline vehicle TOG emissions equal to benzene declines from about 0.03 in 2004 to about 0.02 in 2030). Thus, for the MSAT data presented here, changes in diesel-vehicle emission factors over time for the five gaseous MSATs depend solely on changes in TOG emission factors.

3. RESULTS AND ANALYSIS

Section 3.1 assesses MSAT emissions sensitivity to traffic volumes, fleet composition, and traffic speeds calculated using the TTI speed calculation method. Section 3.2 illustrates the sensitivity of forecasted travel speeds and resulting emissions to speed post-processing techniques (the BPR formula versus the TTI method). Section 3.3 presents MSAT emissions comparisons among project build scenarios for the three analysis years.

3.1 MSAT Emissions Sensitivity to Varying Traffic Speeds and Fleet Mix Assumptions

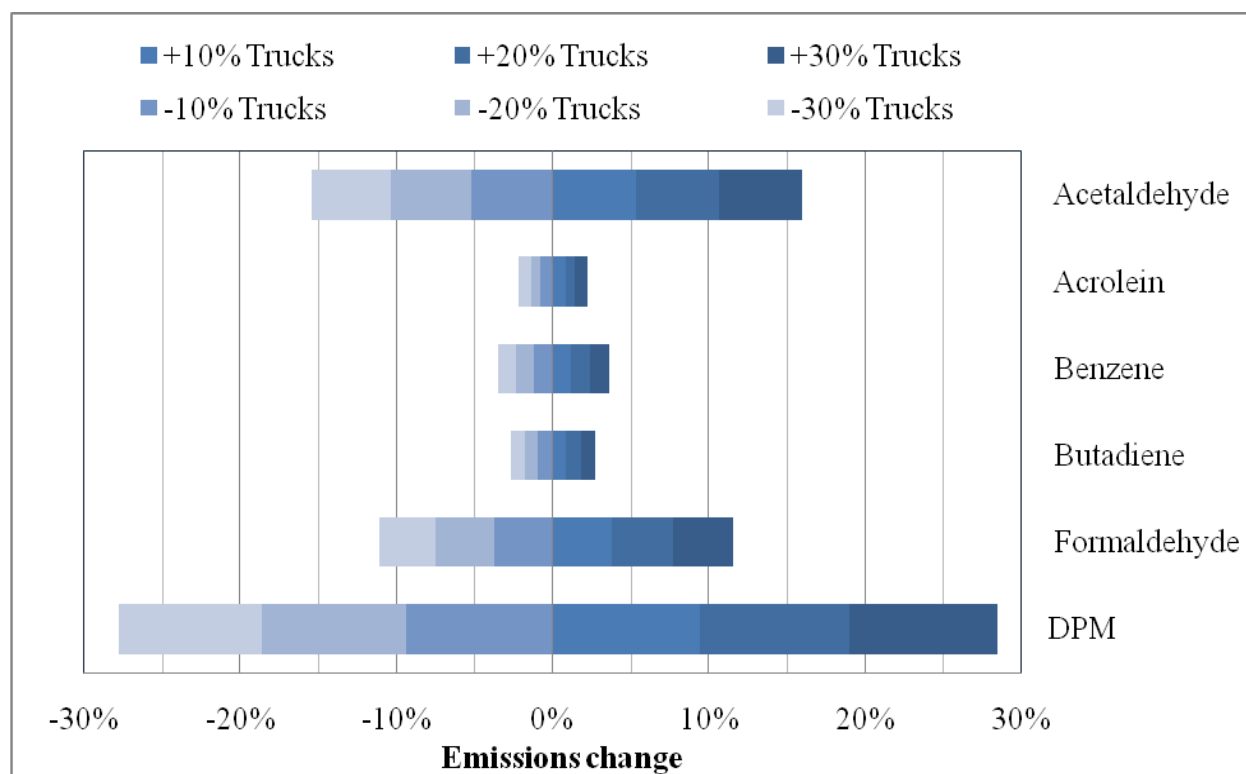
Sensitivity test parameter values (Table 3) were varied to simulate possible project scenarios (e.g., increased volumes due to new lane additions; increased truck percentage given future growth in goods movement; decreased truck percentage due to truck rerouting).

Table 3. Sensitivity analysis: traffic volume, truck percentage and average speed data

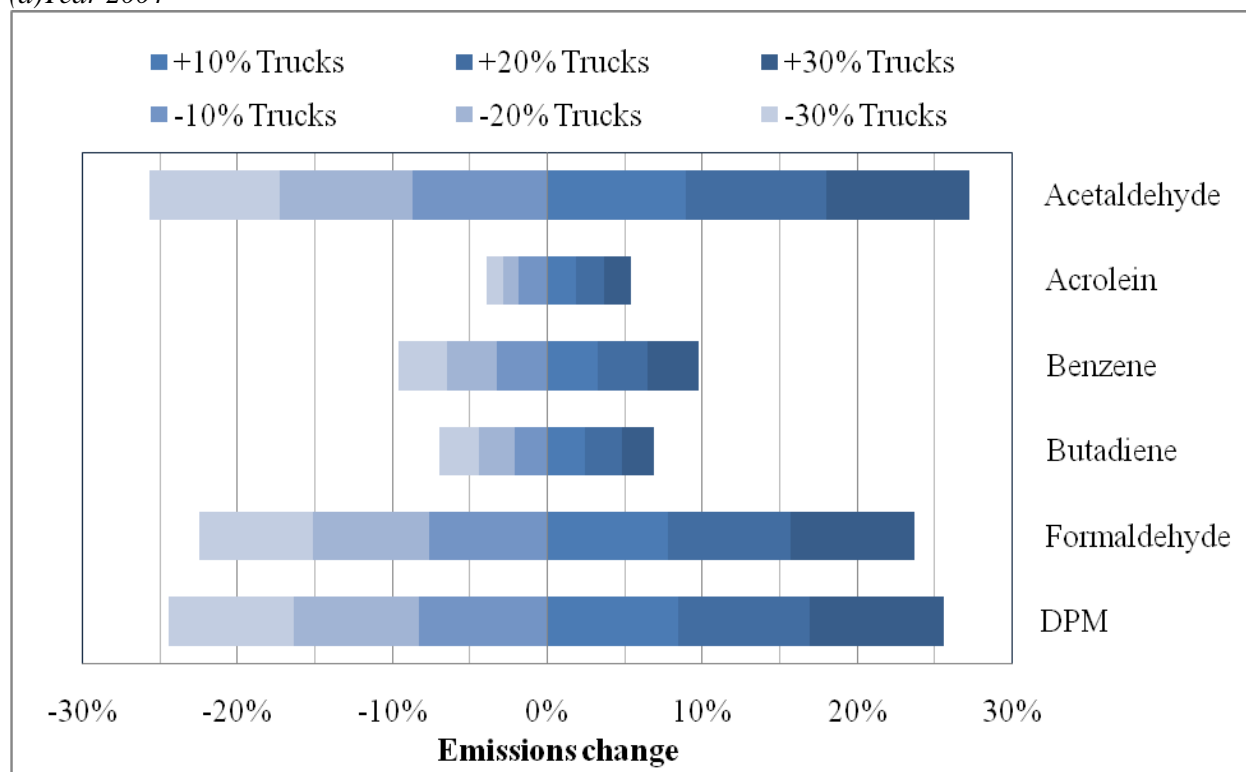
	Year 2004			Year 2030		
%Trucks Change	%Trucks	Speed, mph	Speed Change	%Trucks	Speed, mph	Speed Change
30%	12%	37	-2%	17%	21	-6%
20%	11%	38	-1%	15%	21	-4%
10%	10%	38	-1%	14%	21	-2%
0%	9%	38	0%	13%	22	0%
-10%	9%	38	1%	11%	22	2%
-20%	8%	39	1%	10%	23	4%
-30%	7%	39	2%	9%	23	6%
Volume Change	Volume	Speed, mph	Speed Change	Volume	Speed, mph	Speed Change
30%	16976	20	-46%	21310	10	-53%
20%	15670	26	-32%	19670	10	-52%
15%	15017	29	-24%	18851	13	-41%
10%	14364	32	-16%	18031	15	-29%
5%	13711	35	-8%	17212	18	-15%
0%	13058	38	0%	16392	22	0%

Note: *%Truck Change* means shifting the relative percent allocated to trucks above or below the base case, holding the overall volume constant. *Volume Change* means increasing the amount of vehicles per hour by the percent stated above the base case, holding the truck percent constant. *Speed, mph* refers to the average speed for all vehicles (trucks and non-trucks). Speed estimates are based on the TTI method. *Speed Change* reflects the total percent change from the base case.

Holding truck percentage constant, growth in traffic volume has a significant impact on speeds – up to 53% speed reductions were forecasted due to a 30% growth in volume by 2030. In contrast, variations in truck traffic percentage affected speed estimates only marginally. The impact of fleet mix on emissions of all six pollutants is shown in Figure 4.



(a) Year 2004



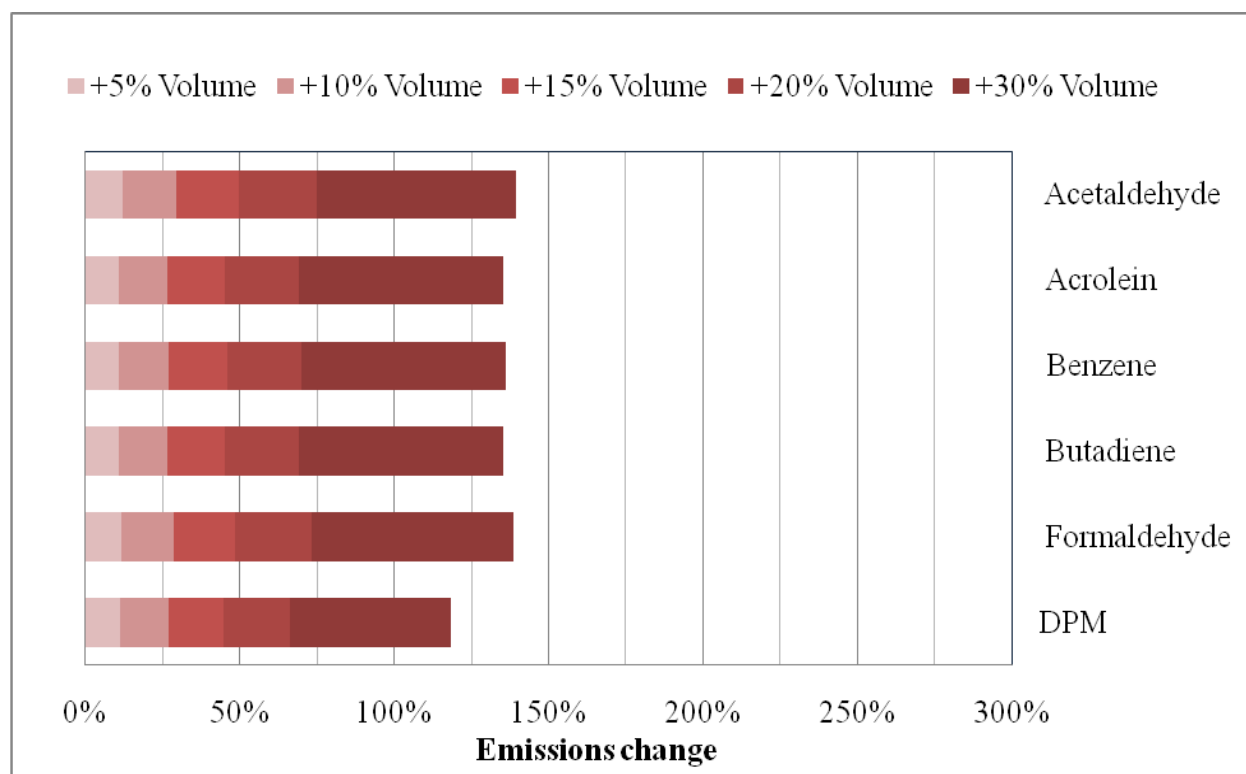
(b) Year 2030

Figure 4. MSAT emissions sensitivity to fleet composition

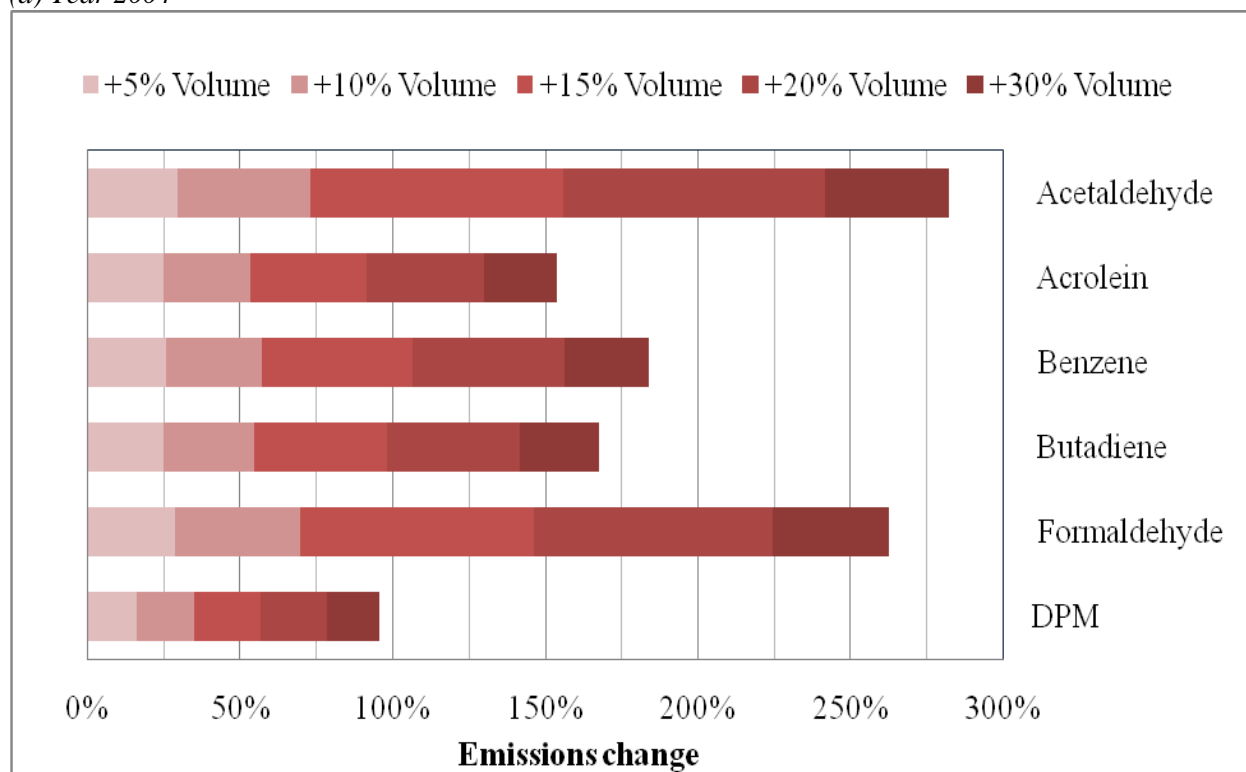
Note: Each increment represents an additional percent change in MSAT emissions associated with the corresponding truck percentage increase or decrease. Shifts in acrolein emissions are associated with gasoline-powered vehicles only.

Changes in fleet composition (i.e., percent trucks) had little effect on calculated average speed, but resulted in substantial shifts in estimated DPM and aldehyde emissions. The relationship between DPM and truck activity is straightforward; the sensitivity of aldehyde emissions to fleet mix is also indicative of the relative importance of trucks to overall aldehyde emissions. Note that total emissions of the five gaseous MSATs became more sensitive to truck percentage over time. Trucks contributed more to overall MSAT emissions by 2030 than in 2004 because their associated emissions declined less significantly than non-trucks (an artifact of data available when CT-EMFAC was created). Therefore, the same scale of truck percentage shift as in 2004 triggered a larger percentage shift in total MSAT emissions by 2030.

Figure 5 shows MSAT emissions sensitivity to total traffic volume for 2004 and 2030.



(a) Year 2004



(b) Year 2030

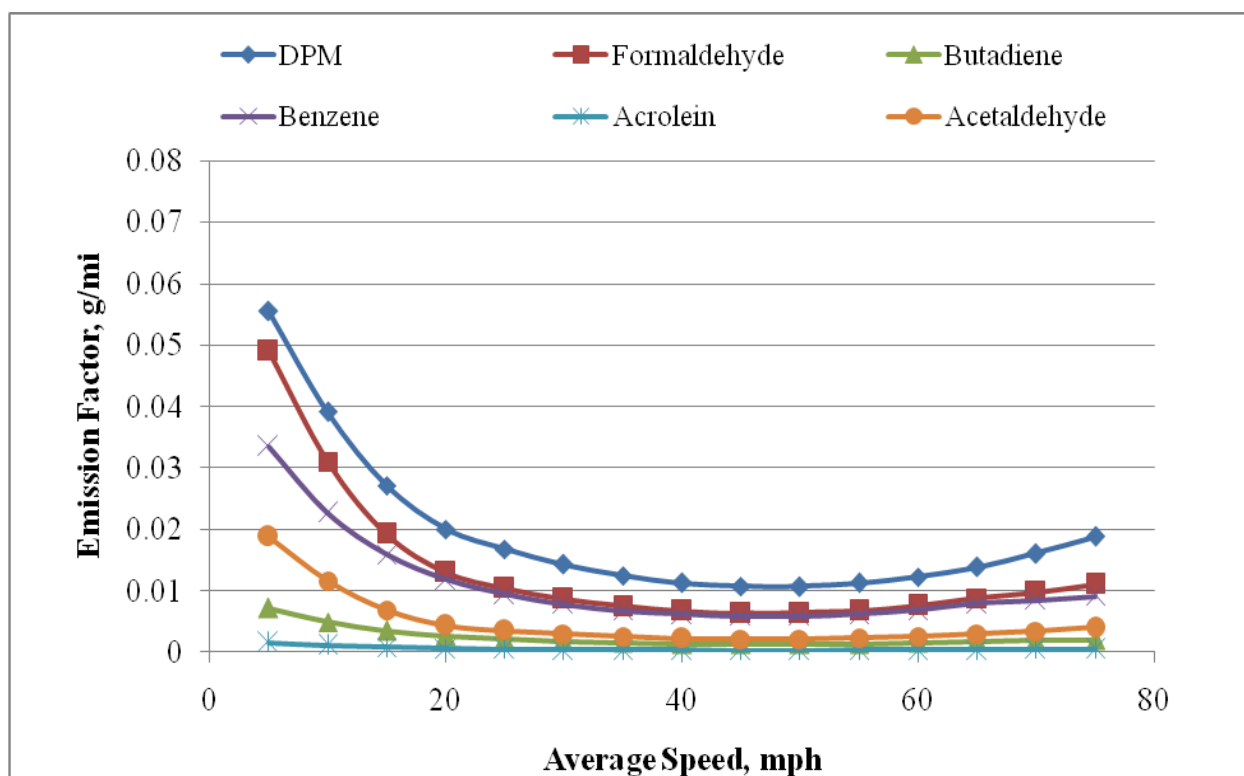
Figure 5. MSAT emissions sensitivity to traffic volume change

Note: Each increment represents an additional percent change in MSAT emissions associated with the corresponding traffic volume increase. Shifts in acrolein emissions are associated with gasoline-powered vehicles.

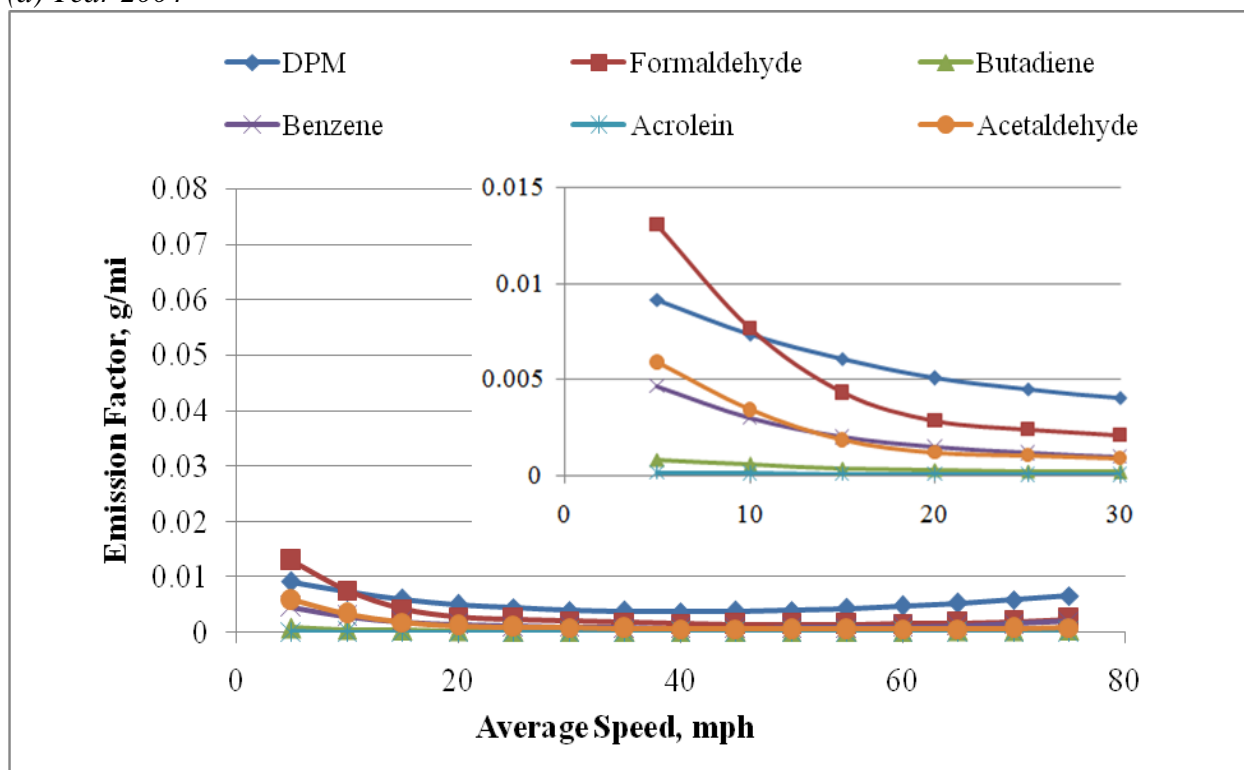
By comparing Figures 4 and 5, it can be seen that, overall, MSAT emissions are more sensitive to changes in traffic volume than to changes in fleet composition. As illustrated in Figure 5, the volume-to-emissions relationship is non-linear and by 2030 emissions increase from approximately 100-250% due to a 30% volume shift, with the greatest increases observed for aldehydes. Note that the calculated travel speeds for a 30% volume increase scenario were 53% lower than for the 2030 base case (see Table 3). The percent shift in emissions that is in excess of the percent shift in volume is a function of the higher grams per mile (g/mi) emission factors associated with the decreased travel speeds.

The base case involved a 26% peak volume increase from 2004 to 2030, substantially lowering the average speed. However, the shift to cleaner-operating vehicles over time overwhelmed the emissions increase due to reduced travel speeds, and overall base case emissions declined from 2004 to 2030. In contrast, within a given calendar year, volume shifts can have a large impact on speeds and emissions. In the 2030 scenario, testing a 30% overall increase in traffic volumes, travel speeds decreased from 22 mph in the base case to 10 mph with the higher volumes. In general, MSAT emissions more than doubled in 2004 and increased by a factor of two to four in 2030 with a 30% volume increase above the base case.

By 2030, the effect of speed on emissions was calculated to be especially important for aldehydes. As shown in the subset of Figure 6b, in the year 2030 aldehydes have emission factor curves with the steepest slopes, meaning a small decrease in speed will lead to a relatively high increase in g/mi emissions.



(a) Year 2004



(b) Year 2030

Figure 6. Speed effect on MSAT emission factors

Note: Figure 6b shows an original plot and a magnified version ($x=30$, $y=0.015$). Shifts in acrolein emissions are associated with gasoline-powered vehicles.

DPM emissions (virtually all of which are emitted by trucks) are less sensitive to total traffic volume changes than other pollutants, which can be explained by the way the sensitivity analysis was performed. Trucks represent only a small portion of the total fleet, so increasing the total volume adds more non-trucks than trucks. In contrast, formaldehyde and acetaldehyde emissions are a function of both truck and non-truck emissions, so shifts in total volume have a greater impact on aldehydes than on DPM.

Note that important differences exist over time in the *incremental* emissions impact of speed changes. In 2004, there are larger emissions impacts for each increment of additional activity and reduced speeds (year 2004 fleet emissions become increasingly more sensitive to speed changes as travel slows). However, this effect diminishes by 2030: as travel speeds slow, the incremental impact from those speed changes decreases. Compare, as an illustration, the impact of the last 10% increment of the 30% volume increase to acetaldehyde emissions in 2004 and 2030: in 2004, this increment produces the largest increase in emissions of the volume scenarios tested (more than double of the preceding 5% increment); in 2030, the last 10% of the 30% volume increment represents the smallest portion of the overall emissions increase (Figure 5). An explanation for this finding is the shortcoming of the TTI speed calculation method discussed in Section 2.2. As a result of Equation 3, the TTI approach assumes that the congested freeway speed estimates will generally not fall below 10 mph on facilities where the free-flow speed is 65 mph. This assumption becomes particularly important by 2030 when travel volumes reach levels at which travel speeds are at the minimum allowed for the TTI method (Figure 7). The result, assuming the TTI formula over-predicts travel speeds in heavy congestion, is likely to be an under-prediction in emissions.

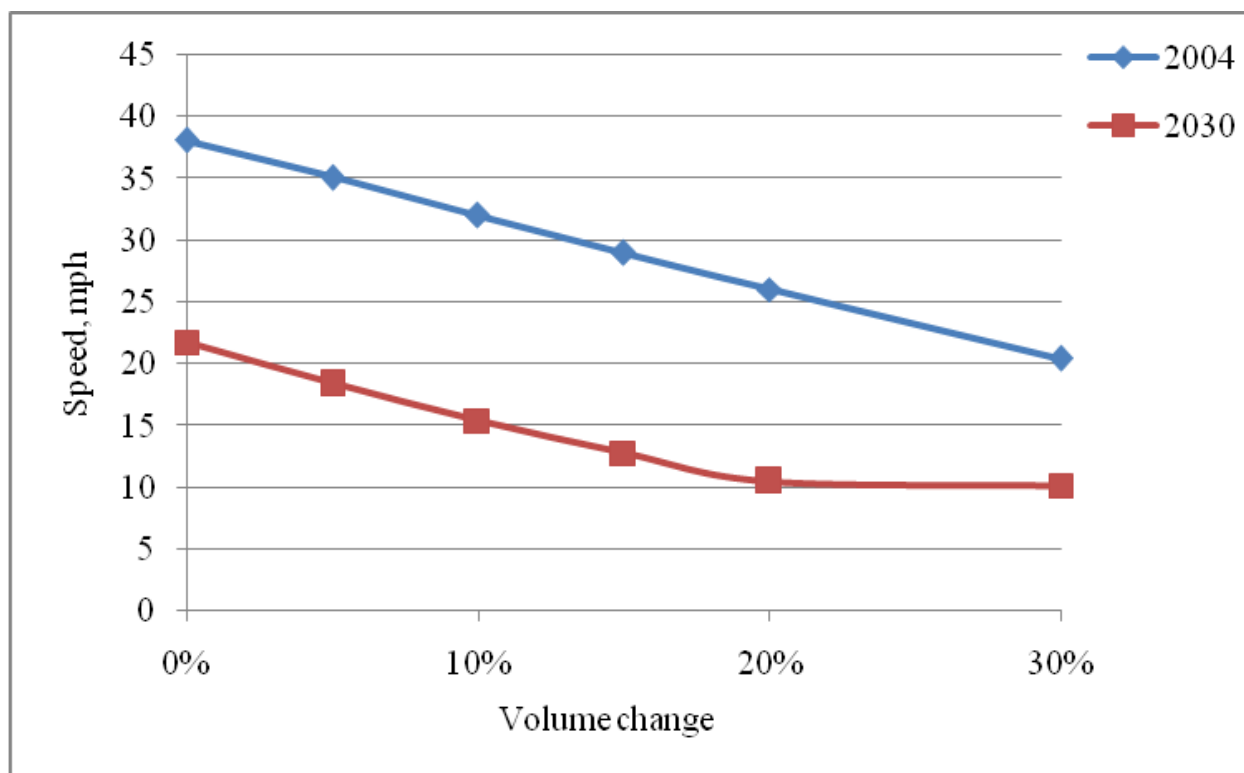


Figure 7. Speed sensitivity to traffic volume change for 2004 and 2030

Note: Speeds were estimated based on the TTI formula.

3.2 MSAT Emissions Sensitivity to Speed Post-Processing Methods

It can be concluded from the previous sections that MSAT emissions are particularly sensitive to traffic speed. In turn, estimated speeds can be especially sensitive to the method used to post-process speed. To further investigate the importance of the method used in speed post-processing, we evaluated how the selection of a speed post-processing technique could affect emissions estimates, holding travel activity assumptions constant. To complete these assessments, the BPR formula was used to calculate travel speeds, and the resulting speeds were contrasted with those obtained using the TTI method. The modeled emissions and the resulting differences from using the two speed post-processing techniques are shown in Figure 8.

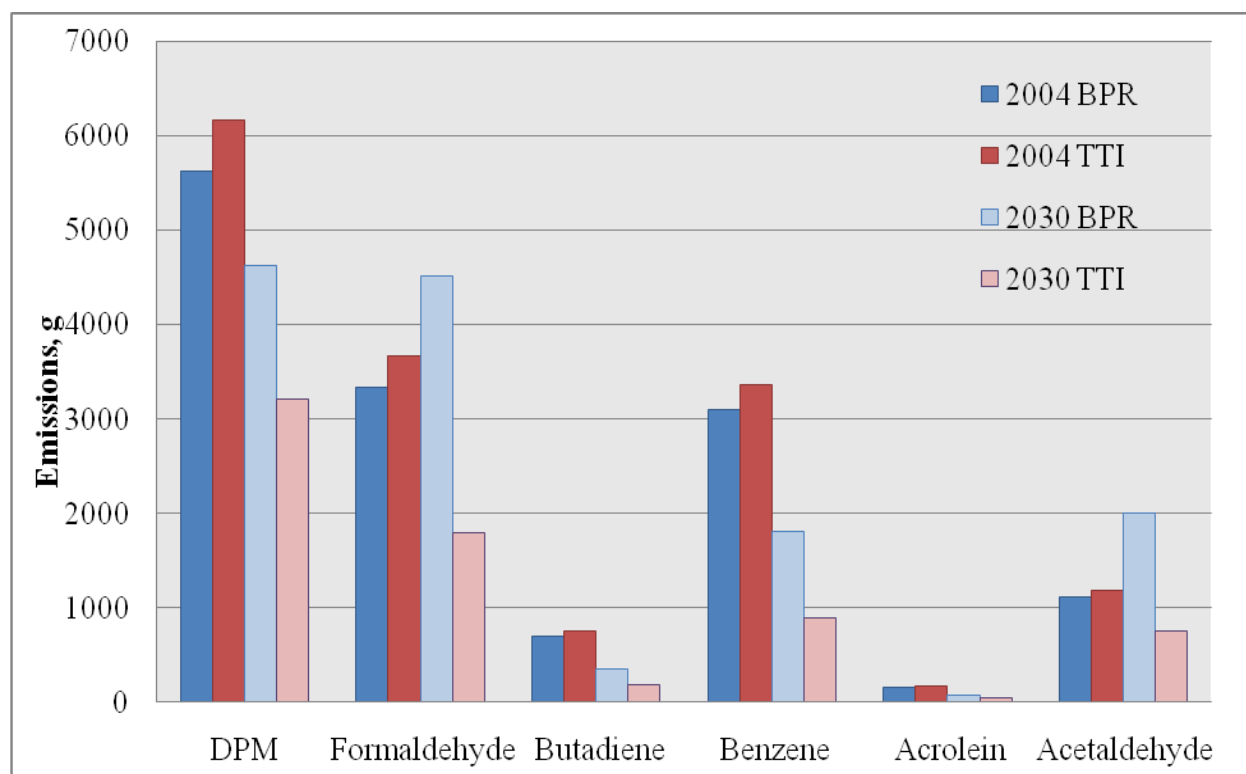


Figure 8. Speed post-processing method effect on MSAT emissions

Note: Emissions modeled are for the base-case 2004 and 2030 scenarios. Shifts in acrolein emissions are associated with gasoline-powered vehicles.

For the year 2004 base case, the speed difference between the two speed calculation methods is within 10%. For the 2030 base case, however, the BPR method resulted in substantially lower travel speeds (average of 11 mph) compared to the TTI-based results (average of 22 mph). As a result, BPR-based emissions ranged from 31% (DPM) to 62% (acetaldehyde) higher than the TTI results. For some pollutants, the difference between the two speed post-processing methods in 2030 is larger than the corresponding emissions reduction that occurred over time (from 2004 to 2030) due to fleet turnover. For example, applying the BPR methodology, the calculated emissions reduction for DPM over time was approximately 18%, a value much lower than the calculated 48% reduction of DPM emissions based on the TTI method (Table 4).

As illustrated by the results in Table 4, the choice of a speed post-processing technique can have important implications for emissions estimates.

Table 4. MSAT emission reductions over time and the difference between TTI and BPR speed post-processing methods

MSAT	Emission reductions over time (2004-2030)		Within-year differences between methods	
	BPR function	TTI method	2004	2030
DPM	18%	48%	9%	31%
Formaldehyde	-35%	51%	10%	60%
1,3-Butadiene	50%	76%	8%	48%
Benzene	42%	73%	9%	50%
Acrolein	55%	77%	8%	45%
Acetaldehyde	-79%	36%	6%	62%

Note: Emissions were modeled for the base-case scenarios. Shifts in acrolein emissions are associated with gasoline-powered vehicles. Reported within-year differences are for TTI compared to BPR; for example, the TTI method resulted in 9% higher DPM estimates in 2004 than the BPR method.

3.3 Scenario Comparison

The estimated MSAT emissions for all project scenarios are shown in Figure 9. Despite a steady increase in forecasted travel volumes and a shift toward a larger fraction of truck traffic (see Table 1), total MSAT emissions decline substantially over time. Generally, reduced g/mi MSAT emission rates due to fleet turnover offset the impact of growth in traffic activity. Note, however, that DPM emissions are projected to slightly increase and constitute over half of the total MSAT emissions in 2013. This is due to the implementation schedule for diesel vehicle emissions standards, as well as the longer lifespan of diesel-powered vehicles (trucks) compared to gasoline-powered vehicles. CARB adopted its “On-Road Heavy-Duty Diesel Vehicles Regulation” in late 2008, and mandated that performance requirements be met beginning 2011.

Therefore, the benefits from this emission reduction program are relatively limited in year 2013. However, by 2030, DPM emissions are projected to decline substantially (Figure 9).

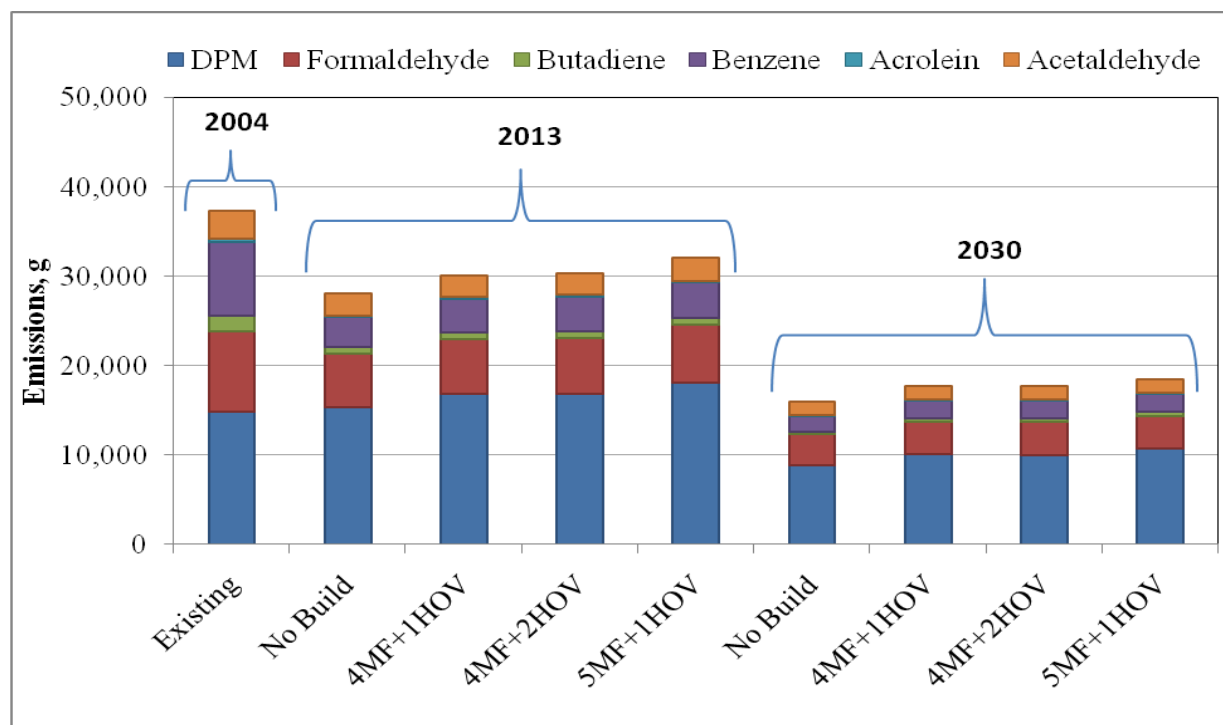
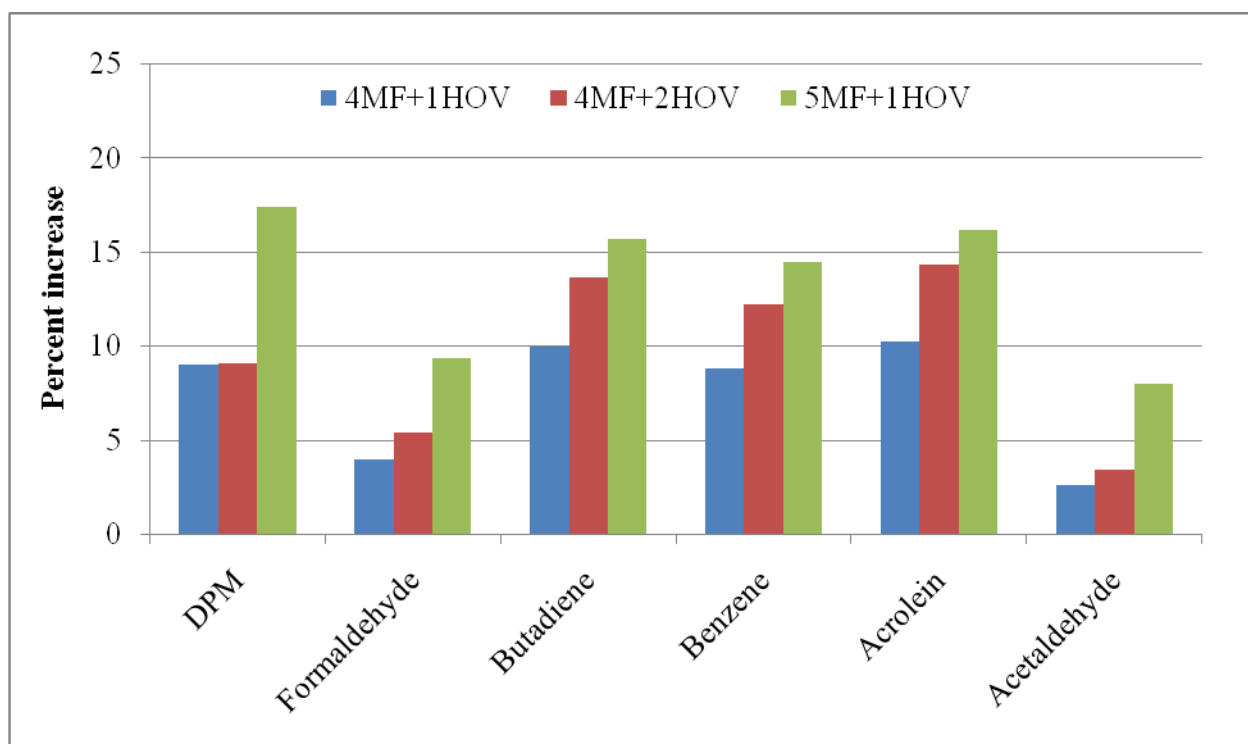


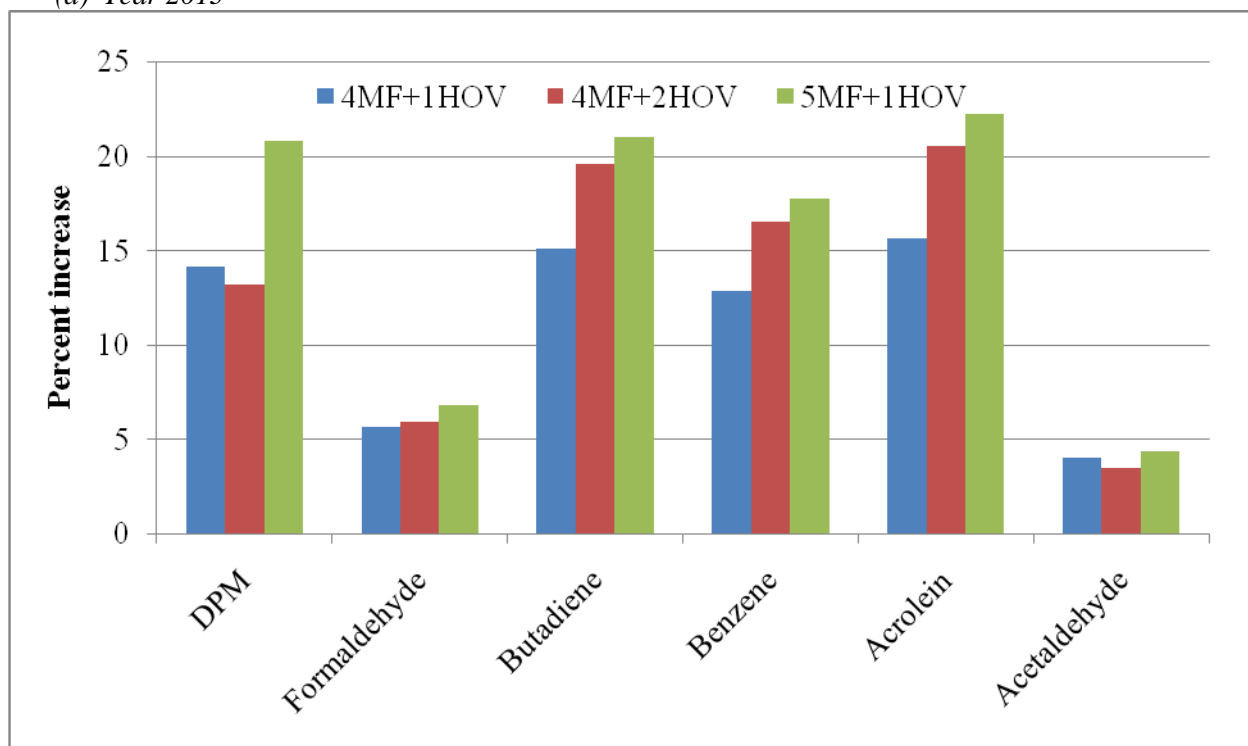
Figure 9. MSAT emissions modeled for all scenarios

Note: Reported acrolein emissions are those associated with gasoline-powered vehicles only. Results include running exhaust emissions only for both peak and off-peak periods.

Within a given analysis year, MSAT emissions are higher for the build alternatives than the no-build scenario, mainly because of the increased traffic volume resulting from capacity expansion. Total traffic volumes are 29%, 34%, and 39% higher for scenarios 4MF+1HOV, 4MF+2HOV, and 5MF+1HOV respectively when compared to a no-build alternative for 2030 (note that the relationship between capacity and volume changes as embedded in the case study, is drawn from real-world project data provided by Caltrans). Figure 10 contrasts build and no-build MSAT emissions for 2013 and 2030.



(a) Year 2013



(b) Year 2030

Figure 10. Emissions increase from the no-build alternative for 2013 and 2030

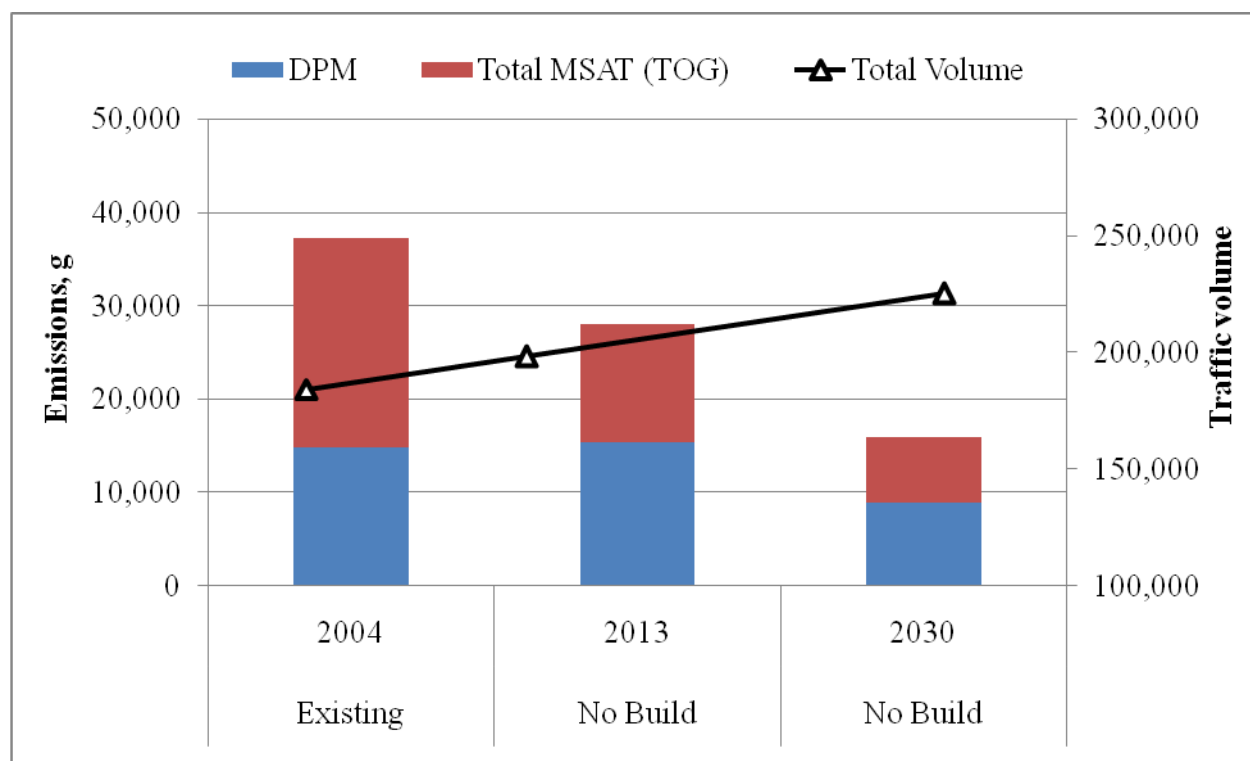
Note: Results include running exhaust emissions only for both peak and off-peak periods.

It can be observed from Figure 10 that the project alternative with five MF lanes and one HOV lane in each direction is associated with a larger emissions increase than other tested build scenarios. This observation can be explained by the fact that, within a given analysis year, the 5MF+1HOV scenario has the highest traffic volume of any of the build alternatives; the increased emissions due to higher traffic volumes offset the emissions benefit from the speed improvements achieved by the increased capacity for this alternative (see Table 1). The increase in emissions is higher in 2030 than in 2013 for most pollutants because, as shown in the sensitivity analysis (see Section 3.1), MSAT emissions changes become more sensitive to volume changes over time.

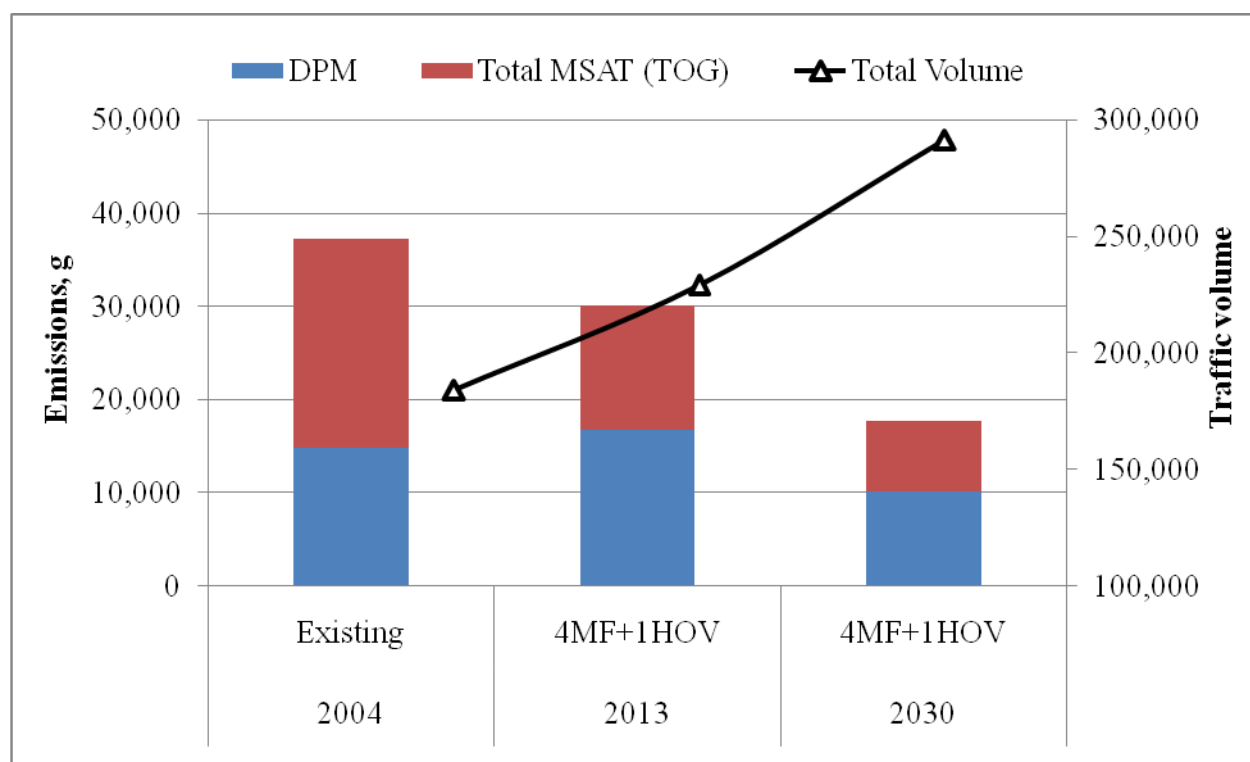
Note that the 4MF+2HOV build option has a smaller emissions increase for DPM relative to the 4MF+1HOV scenario when compared to other pollutants for both years, even though the latter scenario has higher traffic volumes. As noted earlier, DPM emissions are particularly sensitive to fleet composition variations; truck volumes among the build alternatives are projected to be the lowest for the 4MF+2HOV alternative (see Table 1). The difference in how pollutant emissions respond to fleet composition changes is further affected by the emission changes against speed variations.

Figure 11 presents a comparison between the no-build scenario and the build alternative with the lowest emissions in this case study (4MF+1HOV) for years 2013 and 2030. Total traffic volume under the no-build scenario is projected to increase 22% from 2004 to 2030, while total gaseous MSAT and DPM emissions drop 68% and 40%, respectively. In contrast, for the 4MF+1HOV alternative, total traffic volume is projected to increase 58% - more than 2.6 times the growth rate compared to no-build. It is interesting to contrast the differences in the changes in traffic volumes and emissions between the build and no-build cases. Despite the large

difference in traffic volume growth rates between the no-build and 4MF+1HOV scenarios, overall, the decline in emissions from the 2004 base case was relatively similar in both scenarios (MSAT and DPM emissions dropped 66% and 32%, respectively, in the 4MF+1HOV build scenario). In this illustration, a large fraction (but not all) of the emissions increase associated with increased travel volumes was offset by the reduced per-vehicle g/mi emission rates resulting from the build scenario's increased travel speeds.



(a) No-Build Option



(b) Build 4MF+1HOV Option

Figure 11. MSAT emissions and traffic volumes for three project years, for no-build and 4MF+1HOV alternative

Note: results include running exhaust emissions for peak and off-peak periods.

4. CONCLUSIONS AND IMPLICATIONS

MSAT emissions are highly sensitive to key transportation parameters and thus are affected by transportation project design choices. This study used a project-level on-road vehicle emissions modeling tool (CT-EMFAC) to analyze DPM, formaldehyde, 1,3-butadiene, benzene, acrolein, and acetaldehyde emissions sensitivity to traffic volumes, fleet composition, and average speeds for years 2004, 2013, and 2030. Results show that MSAT emissions estimates are highly sensitive to speed changes and that speed impacts can overwhelm impacts from other input parameters, such as traffic volume and fleet mix. The study results imply that project analysts should focus efforts on accurately forecasting traffic volumes, given that volumes, matched with capacity, determine traffic speed.

Although CT-EMFAC reflects California-specific conditions (e.g., vehicle technology, fuel use, and fleet turnover), the relationship between fleet-average emissions and vehicle speeds is generally consistent across modeling tools. Notably, models such as EMFAC (the basis for CT-EMFAC), MOBILE, and MOVES consistently map free-flow travel conditions to g/mi emission rates that are lower than those estimated to occur during congested conditions. Therefore, the results of this California-based sensitivity study are broadly applicable in other states as well.

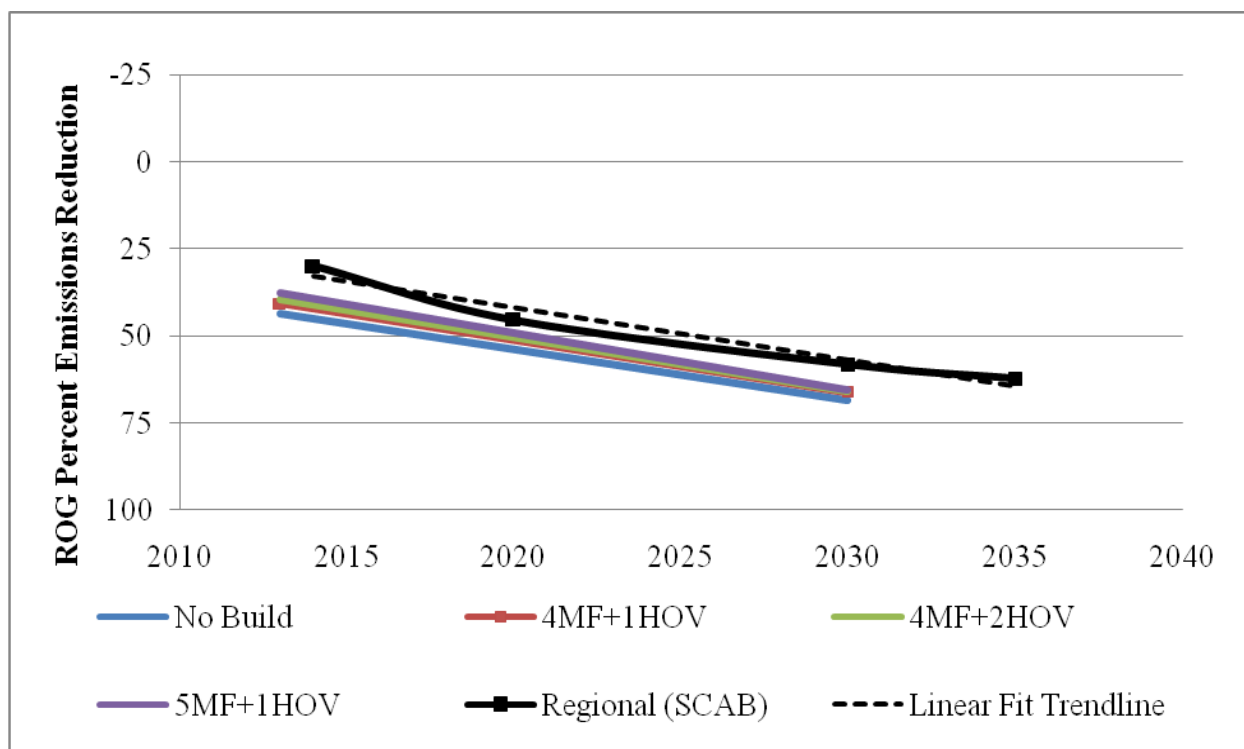
The findings presented here reinforce known principles, such as the decline in fleet-average MSAT emission rates over time due to fleet turnover. In addition, the findings emphasize the importance of a forecasting process rarely discussed in the context of project-level emissions modeling: the selection of appropriate speed post-processing techniques. As demonstrated here, the choice of speed post-processing methods can substantially alter estimated travel speeds and resulting emissions.

The study findings presented here can be enhanced through further research in at least three areas. First, there were important limits to the speciation information available to characterize MSAT emissions. In particular, further work is needed to develop acrolein speciation data for diesel-powered vehicles. Second, since CT-EMFAC was first developed and this work was undertaken, federal guidance has updated the list of priority MSATs project analysts need to address. Effective September 2009, FHWA defined the revised list of priority MSATs to include naphthalene and polycyclic organic matter (POM); acetaldehyde was removed from the priority list (Marchese, 2009). Further work is needed to assess naphthalene and POM emissions. Third, additional research is needed to improve the accuracy of project-level travel activity forecasts for emissions modeling purposes. In particular, guidance is needed to help project analysts apply appropriate techniques to estimate project-specific travel speeds.

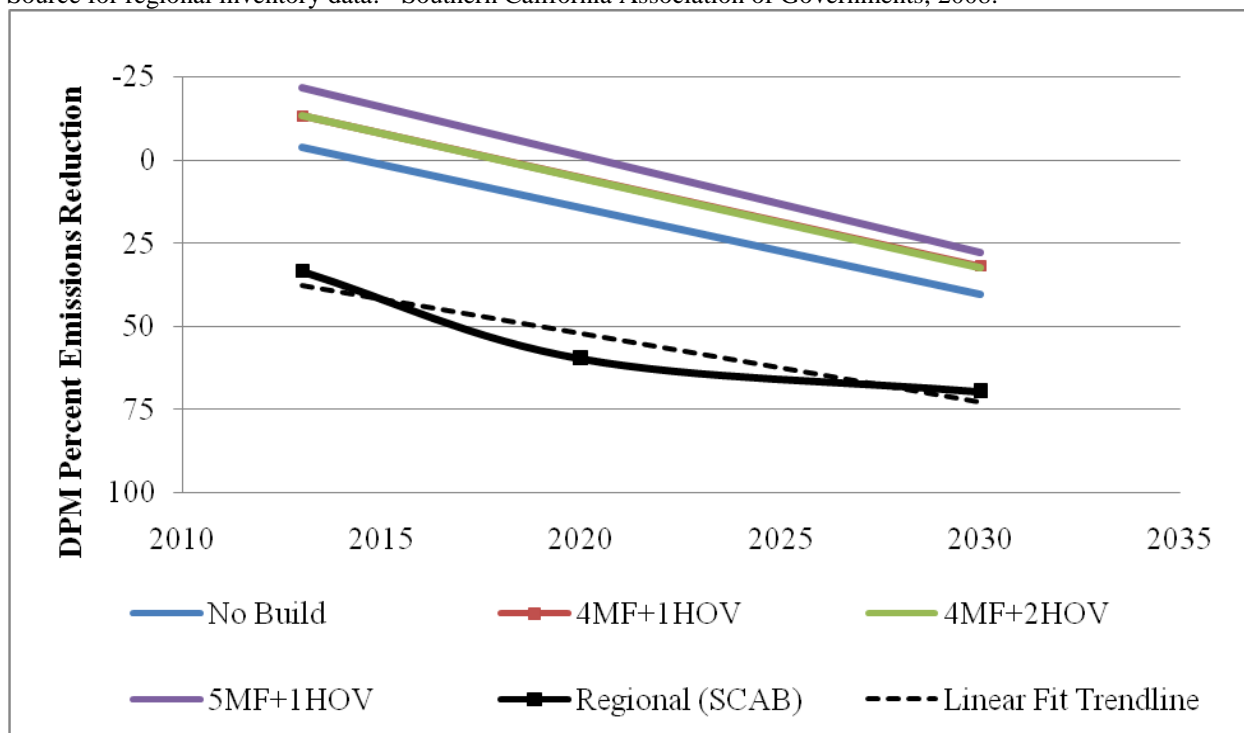
APPENDIX A: PROJECT-LEVEL VS. REGIONAL-LEVEL EMISSIONS TRENDS

To put the results of this study in a broader context, this appendix compares project-level MSAT emissions trends with corresponding trends from regional emissions inventories. Regional emissions inventories are developed to facilitate transportation conformity and state implementation plan (SIP) assessments. This study employed a hypothetical transportation project located in the South Coast Air Basin (SCAB) in southern California, a non-attainment region for ozone and particulate matter. To compare MSAT trends over time between project-level and regional-level scales, we estimated total DPM emissions for SCAB (including running exhaust, idling exhaust, and start exhaust) using the EMFAC2007 model. We also compared the project-level gaseous MSAT emissions data from our case study to a regional reactive organic gas (ROG) emissions inventory prepared in support of transportation conformity assessment for the SCAB region (Southern California Association of Governments, 2008).

Figure A-1 illustrates the trend of regional and project-level MSAT emissions over time (2013-2030). The results show that, despite the variability among the project build alternatives examined here, regional and project-level emissions for gaseous and particulate MSATs trended downward over time at fairly similar rates (i.e., the slopes of the lines are similar). The similarity in the slope of these trend lines is a function of fleet turnover effects on total emissions. The absolute value of changes in project-specific emissions over time varied based on the characteristics of the future-year project scenarios and their activity levels. As seen in Figure A-1b, regional DPM emissions were projected to decrease, in absolute terms, by approximately 70% (2004-2030), while the largest reduction in project-specific DPM emissions modeled here was approximately 40% (2004-2030, no-build scenario).



a). Gaseous MSAT project-level emissions projections compared to a regional ROG inventory.
Source for regional inventory data: Southern California Association of Governments, 2008.



b). DPM project-level emissions projections compared to a regional DPM inventory.
Source for regional inventory data: EMFAC2007, burden mode.

Figure A-1. Project-level MSAT emission reduction over time compared with regional planning emissions inventory (percent reductions are compared to a year 2004 base case)

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